Renewable and Sustainable Energy Reviews 13 (2009) 1437–1445

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Review of feasible solar energy applications to water processes

J. Blanco *, S. Malato, P. Fernández-Ibañez, D. Alarcón, W. Gernjak, M.I. Maldonado

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas-Plataforma Solar de Almería (CIEMAT-PSA), Tabernas (Almería), Spain

ARTICLE INFO

Article history:
Received 25 June 2008
Accepted 9 August 2008

Keywords:
Solar energy
Water processes
Solar desalination
Solar photocatalysis
Solar disinfection

ABSTRACT

In the context of an upcoming energy crisis due to the decline of the Oil Era, water problems are expected to substantially worsen. And vice versa, due to the close relationship between water and energy issues, water problems are also expected to contribute to increased energy problems. Furthermore, environmental considerations, such as global warming, will surely add significant pressure. In this scenario, renewable energies are rapidly increasing their contribution to the global mix, with solar energy clearly having the greatest potential, and in view of the worldwide coincidence that where there is water stress and/or scarcity, there are also good solar radiation levels, the conclusion seems clear suitable technologies must be developed to permit the use of solar energy to simultaneously help solve energy and water problems. The main solar energy applications for water processes presented in this paper are: (i) solar desalination; (ii) solar detoxification and; (iii) solar disinfection.

Contents

1. Introduction: global water and energy problems

Power and water supply are widely recognised as the two major issues mankind will have to face and solve during this century. While it is clear that, in the next few decades, oil will cease to dominate, it is not yet clear today which source of energy will replace it. At the same time, water scarcity, already a serious global problem, will become critical during the first half of this century. Of all the current environmental problems, those related to energy and water are probably the hardest to approach scientifically, and those that will have the worst long-term consequences. Problems associated with water scarcity, and the gradual destruction and contamination of fresh water resources are becoming more pressing in many areas of the planet, causing concern even in countries which, so far, have not experienced such problems.

In 2005, 11,435 million tons oil equivalent (MTOE) of Total Primary Energy Supply (TPES) were consumed [1], with a planned growth of 0.7% in oil production by 2030, when it will start to decline [2], followed by the end of the era of oil as the dominant energy factor in the mid-term, mainly because half of available global conventional oil resources have already been consumed and what remains will be consumed within the coming 40 years. In fact, the most recent world (conventional) oil reserve estimates are (in billion barrels): 1210 [3,4], 1317 [5] and 1120 [6]. Taking an

* Corresponding author. Tel.: +34950387939; fax: +34950365015.
E-mail address: julian.blanco@psa.es (J. Blanco).

1364-0321/$ – see front matter
doi:10.1016/j.rser.2008.08.016

average figure of 1200 billion barrels, and considering the current (heavily increasing) consumption path of nearly 88 million barrels per day (about 32 billion barrels per year) [1], the span is clearly less than 40 years. Possible alternative primary energy sources are also very problematic. Nuclear energy, in addition to strong popular protest in many parts of the world, also has limited long-term fissionable uranium reserves, as well as security concerns (potential fabrication of weapons) in many countries. Coal involves very high CO_2 emissions and its repercussions on climate change [7] are very serious. If the energy prospect is worrisome, problems related to water shortage are even worse. Water is essential to life and today, with more than 6700 million inhabitants in the world today, about 600 million people are already experiencing chronic water scarcity, over 1 billion people lack access to safe drinking water, and unsafe water and poor sanitation cause 80% of all diseases in the developing world. Water tables are falling in the groundwater sources available to about one third of the world's population, in some cases, by 1–3 m a year, as nearly all running surface water is already in use in many parts of the world and over-exploitation of groundwater resources will clearly increase [8]. If the present trend continues, two out of three people on Earth will be living in water-stressed areas by 2025 [9], with the worst impact in arid developing countries where average water availability per person will be only about 15% of the per capita availability in 1950 [8]. Water supply for such large populations is therefore one of the greatest challenges mankind is facing today [10].

In the context of a future energy crisis, water problems are expected to substantially worsen. And vice versa, due to the close relationship between water and energy, water shortages are expected to contribute to increased energy problems and aggravate their consequences. Furthermore, environmental considerations, such as global warming, will surely add significant pressure. The consequences of this analysis are very serious, as the water problem cannot be effectively addressed without considering the implications for energy and the expected growth of human population. Not only will large unavailable additional amounts of water be needed within a few decades, but the energy to produce it will not be easily available. There is therefore no solution to any sustainable water and energy future without the strong participation of renewables in general and in particular, solar energy, which has the highest potential of all the renewable energies [11]. This potential is clearly reflected in Table 1, which shows the estimated theoretical, technical and economic potential of different renewable energy resources, with a total technical potential of about 85 TW. By comparison, the total primary energy consumption in 2005 (11,435 MTOE) as mentioned above, is equivalent to 15.18 TW. Estimated global energy consumption to 2050 is 25–30 TW, reaching 40–50 TW by 2100 [12]. Until the hypothetical arrival of fusion energy in the distant future, only solar energy has the potential to amply surpass this figure (60 TW of technically feasible estimated potential) [13].

Therefore, as solar energy has the highest potential of all the renewables, and also, in view of the worldwide coincidence that where water stress and/or scarcity exists, there are also good levels of solar radiation, the conclusion seems clear. Suitable technologies must be developed to permit the use of solar energy to simultaneously help solve energy and water problems. The main solar water process applications, under scientific and technological development at *Plataforma Solar de Almeria*, are the following:

(a) Solar Desalination, from two different approaches, combined solar power and desalination plants (MW range), and medium to small solar thermal desalination systems (kW range).
(b) Solar Detoxification, by making use of the near-ultraviolet and visible bands of the solar spectrum (wavelengths shorter than 390 nm for TiO_2 and 580 nm for photo-Fenton) to promote a strong oxidation reaction by generating oxidizers, either surface-bound hydroxyl radicals ($OH^{\bullet}$) or free holes, which attack oxidizable contaminants, producing a progressive break-up of molecules yielding CO_2, H_2O and dilute mineral acids.
(c) Solar Disinfection, which applies the detoxification techniques mentioned above, using a supported photocatalyst, to generate powerful oxidizers to control and destroy pathogenic water organisms.

2. Solar brackish and seawater desalination

The recent United Nations Human Development Report 2006 [16] alerts against an unprecedented crisis in coming years as a consequence of a growing scarcity of fresh water per inhabitant in developing countries. It forecasts that in the next twenty years, the average world water supply per inhabitant will decrease by one third, due mainly to the growing world population, environmental pollution and climate change. In the second half of this century, in the worst-case scenario, seven billion people in 60 countries are expected to face a water shortage problem. In the best-case, this scarcity will affect two billion people in 48 countries, depending on factors such as the world population growth rate and the implementation of appropriate corrective policies.

The solutions for alleviating this water shortage problem go from the necessary savings in all consumer sectors to promotion of surface groundwater treatment techniques, and reuse of wastewater [17]. However, there are areas on the planet (very arid or isolated) that require outside contributions for their development. In this case, desalination, and especially seawater desalination, is proposed as one of the main alternatives for solving the problem [18]. Desalination is quite often not just an interesting alternative, but the only feasible and practical option, as more than 70% of world population lives in a 70 km strip bordering the seas [18]. In 2003, world installed desalination capacity was 37.75 hm^3/day [19]. 64% of this is for seawater, with 10,350 plants having a

Table 1
Yearly estimated potential of different renewable energies (1 TW = continuous power production of 1 TW during the year = 8760 TWh = 31.53 exajoules) [13–15]. Total primary energy consumption in 2005 = 15.18 TW [1].

	Gross theoretical useful potential	Technically feasible potential	Current economic potential	Total installed capacity (2003)
Biomass	8–14 TW	6–8 TW	No data[a]	1.6 TW
Hydraulic	4.6 TW	1.6 TW	0.8	0.65 TW
Geothermal	66 TW	11.6 TW	0.6 TW	0.054 TW
Wind	20 TW	2 TW	0.6 TW	0.006 TW
Solar	600 TW	60 TW	0.15–7.3 TW	0.005 TW
Ocean	234 TW	No data	No data	–
Total	1030 TW (approximately)	85 TW (approximately)	7 TW (approximately)	2.3 TW (approximately)

[a] Water availability may become an important limiting factor.

capacity of over 100 m^3/day. Today, total production of desalinated water covers the necessities of about 100 million people [20].

Seawater desalination has been shown to be the only alternative for many regions in the world such as the Persian Gulf, the Mediterranean Sea and the Caribbean, and is also an important source of fresh water in many other areas of the world. Despite the advances in energy efficiency during the last decade, seawater desalination continues to be an intensive consumer of fossil fuels. Furthermore, the majority of these areas have large amounts of solar energy available and, taking the energy situation into consideration, the solar-driven desalination option not only seems completely logical but, in the mid range, absolutely necessary. It is also clear that scientific and technological developments are still needed to make them economically feasible.

2.1. Solar thermal desalination

For large desalinated water production volumes, the best option is indirect solar desalination [21], which consists of hooking up a conventional distillation plant to a solar collector field providing the thermal energy required for multi-stage flash (MSF) or multi-effect distillation (MED). Conventional MSF plants, for reasons such as cost and apparently high efficiency, pushed out MED systems in the 1960s, and only small MED plants were built. However, in the last decade, interest in multi-effect distillation has been significantly renewed and the MED process is currently competing technically and economically with the MSF technology [22,23]. Recently, the "Enhanced Zero Discharge Seawater Desalination using Hybrid Solar Technology" project (AQUASOL), mainly for developing an improved-cost and energy-efficient MED solar desalination technology (Fig. 1), was concluded at the Plataforma Solar de Almería.

The AQUASOL project was the continuation of long previous research in solar desalination at the Plataforma Solar de Almería, and widely reported in many previous papers [24]. The project focused on the development of specific technological aspects that are expected to significantly improve the present technical and economic efficiency of solar MED systems and thereby reduce the cost of water production. The main plant subsystems are:

- A multi-effect distillation plant (14 effects, 3 m^3/h nominal distillate production).
- A stationary 500 m^2 CPC (Compound Parabolic Concentrator) solar collector field (Fig. 2).
- A water thermal storage system (total volume: 24 m^3).
- A Double-Effect (LiBr-H_2O) Absorption Heat Pump (DEAHP) for heat recovery from the last MED effect (leading to a significant increase in overall process efficiency).
- A smoke-tube gas boiler.
- An advanced solar dryer for brine treatment and final salt production.

Fig. 1 shows the configuration and interconnection of these main subsystems. The overall system was designed to operate in three modes depending on the heat source [25]:

- Solar-only mode: energy entering the first distillation effect comes exclusively from thermal energy from the solar collector field.
- Fossil-only mode: the double-effect absorption heat pump (DEAHP) supplies all of the heat required by the distillation plant.
- Hybrid mode: the energy comes from both the heat pump and the solar field. Two different operating philosophies were initially considered here:
  - The heat pump works continuously 24 h a day with a 30% minimum contribution.
  - The pump is started up and shut down on demand, depending on the availability of the solar resource.

Other interesting solar desalination technology options, also under development at PSA, are air-gap membrane distillation [26]

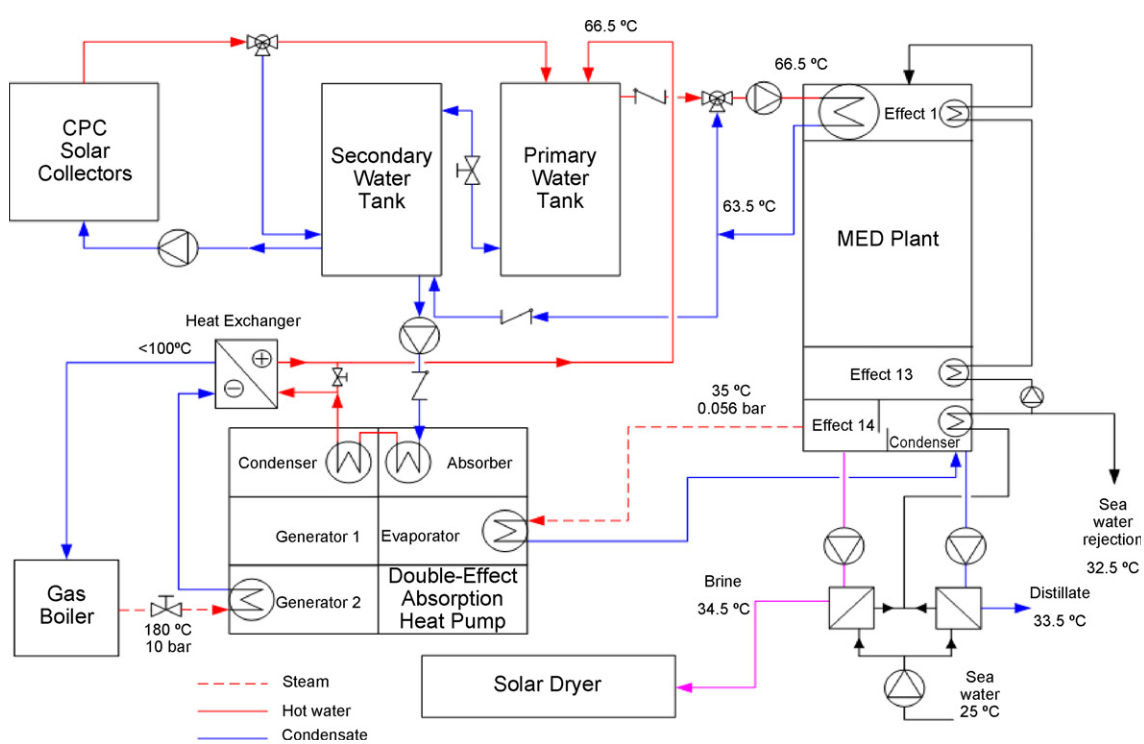

Fig. 2. AQUASOL 500 m^2 stationary CPC solar collector field.

and combined solar thermal and reverse osmosis using an organic Rankine cycle [27].

2.2. Integration of desalination processes in concentrating solar power plants

MW scale solar power generation using Concentrating Solar Power (CSP) technology may be by any of the four basic types being promoted internationally: central receivers, parabolic troughs, parabolic dishes and linear Fresnel systems. All of them are based on glass mirrors, which continuously track the position of the sun to attain the desired concentration ratio. The concentrated sunlight is absorbed by a tube specially designed to reduce heat loss. Heat transfer fluid (e.g., oil) flows through the absorber tube and transfers the heat to a power cycle, where high-pressure high-temperature steam is generated to drive a turbine in a conventional power cycle. Recently, direct steam generation is also being used for power production.

Several different basic conventional co-generation power-desalting plant (CPDP) configurations are possible for generating electricity and producing fresh water from seawater [28]: (i) MSF units operating with steam extracted from steam turbines, or supplied directly from boilers; (ii) low-temperature multi-effect boiling (MED), using steam extracted from a turbine and; (iii) seawater RO desalting units supplied with electricity from a steam power plant or from a combined gas/steam power cycle. In Gulf countries, most power plants are co-generation power desalting plants that integrate the three conventional (MSF, MED and RO) desalination technologies at different levels. The preference of one scheme over another would depend on many factors, such as the required power to water ratio, cost of fuel energy charged to the desalting process, electricity sales, capital costs, and local requirements [29]. In the last few years, hybrid desalination systems combining both thermal and membrane desalination processes with power generation systems have also been considered an economical alternative to traditional dual-purpose evaporation plants. Hybrid (membrane/thermal/power) configurations are characterized by flexible operation, low construction cost, lower specific energy consumption, high plant availability and better power and water matching [30]. However, it has also been shown that most existing dual-purpose power-desalination plants are far from optimized for energy and their overall efficiency still has much room for improvement [31]. The idea of integrating desalination in solar power plants is therefore very attractive as there is usually abundant solar radiation at places where fresh water is scarce.

Solar power-water co-generation plants (CSP + D) are therefore a very attractive concept as, potentially, it could solve power and water problems in many arid and semi-arid areas of the world. For dual-purpose power and water plants, combined gas and steam turbine cycles are the most efficient for power production, and MED is the most efficient thermal desalination technology. Therefore, the combination of a solar field and a combined cycle power plant in an integrated solar combined cycle power plant (ISCC) is a good way to reduce the cost of solar generation through the use of common infrastructure and the economics of scale of the steam turbine. Although the ratio of solar to fossil generation is low in an ISCC, the absolute solar electricity generated (in kWh) is higher for a given incremental investment than in a solar Rankine cycle power plant.

This configuration, in which an MED unit replaces a conventional water cooling system for condensation of turbine exhaust steam (Fig. 3), although it is one of the first basic CSP + D plant designs, it is not necessarily the best one, because in most cases, the water produced does not compensate its reduction in electricity production. Consequently, other possible configurations (such as the merging of combined cycles and heat pumps) are more attractive than the one in Fig. 3.

CSP + D power plant potential is very high, and even more so thermodynamically, and depending on the selected configuration, perfectly logical. CSP is already a reality in countries such as Spain, and could cover 14% of the electricity demand of MENA (Middle East and North African) countries by 2025. By 2050, it could become the dominating power source in the region with a 57% share at an estimated cost in the 8 c€/kWh-to-15 c€/kWh range [31]. More R&D and Demonstration would be needed, but the steep rise in oil price, already pressuring to reduce the cost of conventional power and energy-intensive desalination systems, is a major force in promoting such initiatives, as CSP technology is a very promising alternative to the problem [32]. Land required by these technologies for the concentrating solar thermal collector array to desalinate 1 billion m^3/year would be approximately 10 km $\times$ 10 km, which is about 10 m^3 of desalinated water per square meter of collector area [31].

3. Solar water photocatalytic applications

3.1. Fundamentals

The involvement of sunlight in the removal of synthetic chemicals from the environment is well documented in the many papers published in recent years [33], "Advanced Oxidation Processes" (AOPs) have become important hazardous water pollution treatment techniques, with an increasing number of technically and economically feasible applications [34]. The main reason for the use of AOPs is usually severe water pollution and/or

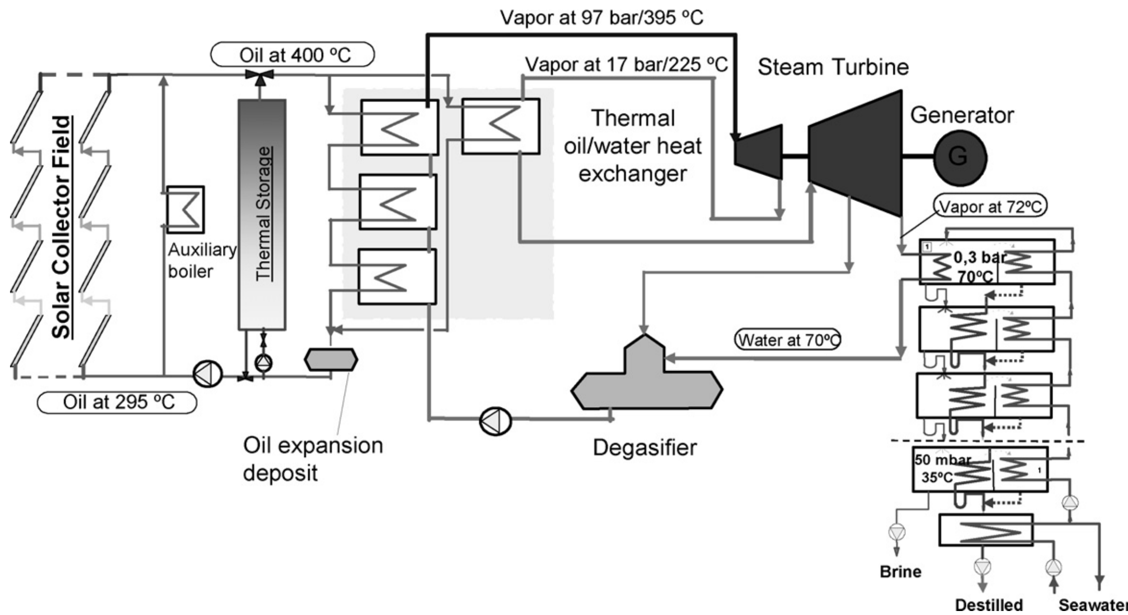

Fig. 3. Basic schematic diagram for a 100-MW combined solar power (Rankine cycle) + desalination plant, in which the condenser system is replaced by an MED desalination system.

toxicity which cannot be treated biologically. All AOPs are based on the generation of powerful oxidant radicals, and "Photocatalytic Oxidation Processes" (PCOs) are usually included among the AOPs, along with other radical-promoting processes like plasma, electron-beam, etc. The main advantage of PCOs over other AOPs is their potential for using solar energy in the form of solar photons (e.g., in solar detoxification), whereby degradation becomes more environmentally significant.

To date, the PCO processes most widely studied and developed for the solar decontamination of water effluents have been heterogeneous TiO_2 with persulfate enhancement and homogeneous photo-Fenton (Table 2) [35]. Both processes make use of the most energetic part of the solar spectrum near the ultraviolet/visible light in a very strong oxidation reaction which takes place when the radiation activates a photocatalyst in the presence of oxygen. This generates hydroxyl radicals ($^{\bullet}OH$) that attack any organic compound in the medium, gradually causing bonds to break and turning into compounds such as carbon dioxide and water.

The powerful oxidation capacity of hydroxyl radicals is given by its high oxidation potential (E_o = 2.8 V vs. NHE), which is much higher than other conventional oxidants such as ozone (E_o = 2.07 V), hydrogen peroxide (E_o = 1.78 V), chlorine dioxide (E_o = 1.57 V), chlorine (E_o = 1.36 V), etc. It is therefore able to react with almost any organic aromatic compound and, consequently, photocatalytic processes can be applied to hazardous non-biodegradable water contaminants having no easy conventional treatment at maximum organic concentrations of several hundred mg L^{-1}. The process is also valid for complex mixtures of organic contaminants. Some examples are hazardous pollutants, such as phenols, agrochemical wastes, halogenated hydrocarbons, industrial pharmaceutical biocides, wood preserving waste, hazardous metal ions, cyanides, aqueous munitions waste, etc. [36]. Other applications of interest are treatment of polluted groundwater, seaport tank terminals, cleaning landfills, etc.

Table 2
Photocatalytic oxidation processes that can be driven by solar energy.

TiO_2-persulfate photocatalytic system ($\lambda < 390$ nm)	Photo-Fenton method (H_2O_2 and Fe^{2+}) irradiated in the UV–vis range ($\lambda < 580$ nm)
$TiO_2 + h\nu \rightarrow e^-_{CB} + h^+_{VB}$	
$h^+_{VB} + H_2O \rightarrow {}^{\bullet}OH + H^+$	$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + {}^{\bullet}OH$
$S_2O_8{}^{2-} + e^-_{CB} \rightarrow SO_4{}^{\bullet-} + SO_4{}^{2-}$	$Fe^{3+} + H_2O + h\nu \rightarrow Fe^{2+} + H^+ + {}^{\bullet}OH$
$SO_4{}^{\bullet-} + H_2O \rightarrow {}^{\bullet}OH + SO_4{}^{2-} + H^+$	

3.2. Solar photocatalytic water treatment plants

Solar photocatalytic treatment plants are usually operated in batch mode. Polluted water must first be pre-treated so the organic destruction process takes place under the best possible conditions. After this, the catalyst is added and the mixture is pumped in batches through the chemical reactor (solar collector field) until the pollutants are degraded. Depending on the nature of the contaminants to be treated, some potentially useful chemical oxidants can be added to enhance process efficiency. When the process is complete, post-treatment processes must adjust the water chemistry to conditions suitable for discharge. When industrial wastewater is followed by biological treatment [37], post-treatment could be reduced to a mere pH adjustment and catalyst recovery.

Fig. 4 shows the conceptual design of the solar photocatalytic treatment plant developed to treat wastewater from recycling pesticide bottles (Albaida plant, Almeria, Spain). The water from washing the pesticide bottles is treated in batches until 80% of the TOC has been mineralized. At this point, the water is transferred to the post-treatment (iron precipitation, sedimentation and recuperation), and either reused for bottle washing or discharged for irrigation through an activated carbon filter to ensure discharge quality. The water for reuse is pumped back to wash the shredded plastic until TOC is 100 mg L^{-1}. In this closed cycle, water may be reused up to about 10 times before final discharge. About 95% of the contaminants are mineralised and a granulated activated carbon filter removes the remaining 5% [38]. The solar photocatalytic treatment plant is provided with fully automatic control systems for minimum operation and maintenance requirements. The level of water treatment is indirectly measured by measuring sunlight availability. About 75% of the total volume of the

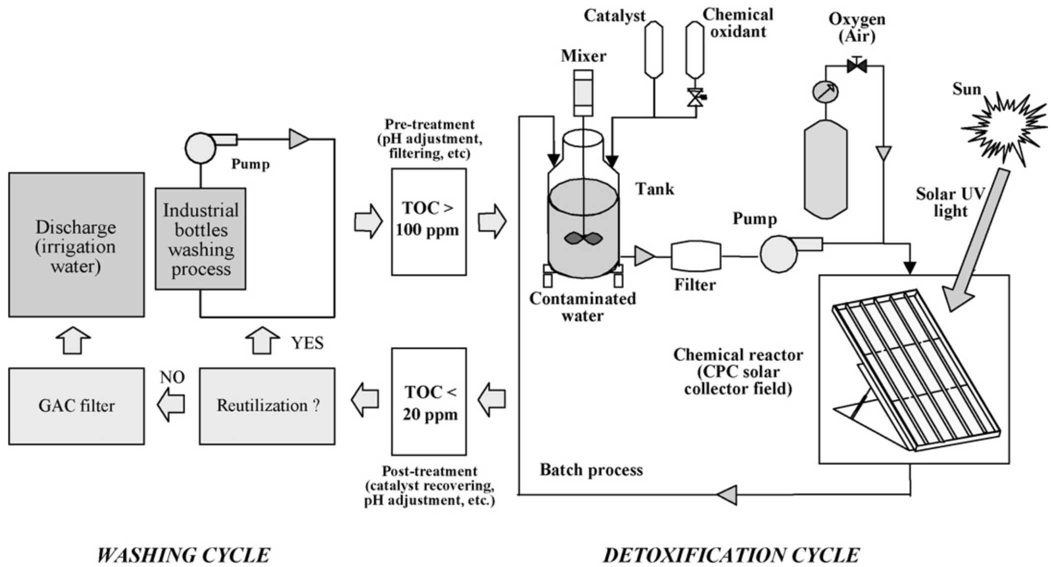

Fig. 4. Conceptual design of the ALBAIDA solar photocatalytic plant for the treatment of wastewater from washing shredded plastic pesticide bottles for recycling.

treatment circuit is continuously exposed to sunlight in 150 m^2 of CPC solar reactors. Once the desired destruction is achieved, the water is transferred to the catalyst separation tank, and the treatment circuit is filled again with new wastewater to be treated, restarting the process. A programmable logic controller controls all operating procedures and sequences. Initial market analyses show a number of suitable applications for this remarkable environmental technology, treatment of pesticides being one of the most promising (Fig. 5).

Partial oxidation of toxic compounds by AOPs has been shown to substantially increase wastewater biodegradability. Even though AOPs for wastewater treatment have been proven to be highly efficient, their operation is currently quite expensive (tens of €/m^3). The combination of a solar AOP as a preliminary treatment, followed by an inexpensive biotreatment, would therefore seem to be an economically attractive option. Recently (2006), a new step successfully combines solar photo-Fenton and aerobic biological processes to treat industrial saline wastewater containing about 0.6 g/L of a nonbiodegradable compound (α-methylphenylglycine, MPG) and 0.4–0.6 g/L TOC. It consists [39] of a solar photo-Fenton reactor with 100 m^2 of CPCs and an aerobic biological treatment plant based on a 1 m^3 capacity immobilized-biomass reactor. The combined system efficiency was about 95% mineralization. 50% of the initial TOC was degraded in the photo-Fenton pre-treatment, while 45% was removed in the aerobic biological treatment.

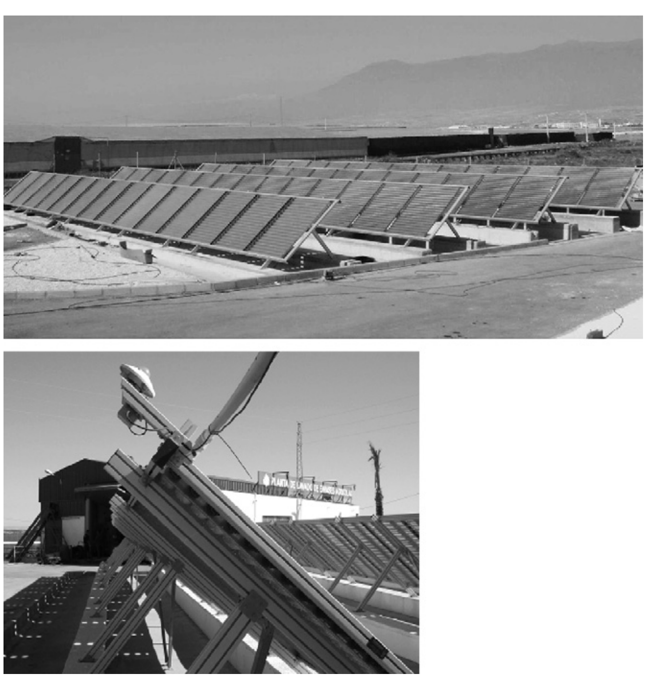

Fig. 5. Two views of industrial solar photocatalytic water treatment plant for pesticide bottle recycling (La Mojonera, Almería, Spain).

4. Solar water disinfection

4.1. Fundamentals

Poor-quality drinking water or inadequate treatment is one of the greatest predictable causes of early death in the world. This is because water is one of the major vehicles of contagion. According to the World Health Organisation, polluted drinking water is responsible for about five million deaths per year worldwide, and a fatal childhood risk factor. Every 8 s, a child dies from a water pollution-related disease. And this problem is not limited to developing countries. Even in OCDE countries, there are often outbreaks of such diseases [40]. The most commonly used disinfection methods are based on chlorination, in which diluted chlorine or gas, efficiently fights viruses and bacteria. However, these methods generate highly toxic by-products, such us trihalomethanes and other carcinogenic compounds.

The bactericidal effect of solar radiation, first reported by Downes and Blunt in 1877, makes use of the ultraviolet range of the solar spectrum, which is limited to wavelengths over 290 nm. The instantaneous solar irradiation in a given location depends on the solar height and can vary by a factor of 2–100. Of all the solar radiation that reaches the Earth's surface, less than 10% is UV light, of which only a small part is useful for water disinfection. In spite of this, much has been published on treatment of water contaminated by organic compounds and microorganisms based on exclusive use of solar radiation [41]. It has been demonstrated to eliminate a large number of organic and pathogenic organisms, avoiding generation of the toxic by-products typical of conventional technologies. The rate of bacterial decontamination by solar

radiation is proportional to radiation intensity and temperature, and inversely proportional to the depth of the water, due to light dispersion. The amount of radiation attenuated by this depends on the wavelength range. For example, between 200 and 400 nm, the reduction is less than 5% m^{-1} depth, and at longer wavelengths it may be up to 40% m^{-1} [42].

The most destructive wavelengths for microbial life are in the near UV-A spectrum (320–400 nm), whereas the spectral band from 400 to 490 nm is the least harmful. Likewise, differences in bacterial inactivation rates at temperatures between 12 and 40 °C are negligible, but the bactericidal action is accelerated twofold when the temperature rises to 50 °C, probably due to the synergetic effect between radiation and temperature [43]. Joyce et al. report very promising results with disinfection of water with high concentrations of faecal bacteria (10^6 CFU/mL, colony-forming units per mL) making use of the bactericidal effect of solar heating at a maximum of 55 °C [44]. Recent publications, such as those by Rincón and Pulgarin [45–48] analyse the role of different parameters on photocatalytic bacteria disinfection. Light intensity, intermittence of light, presence of electrolytes and dissolved organic matter, use of real water and distilled water, and different types of catalyst have been studied exhaustively in their research. New studies on solar disinfection done at the Plataforma Solar de Almería with *E. coli* and *Fusarium* spp. focus on the study of the influence of different operating parameters [49–52].

4.2. Research activities and applications

The European Union International Cooperation programme (INCO) has recently sponsored two different projects for developing a cost effective technology based on solar photocatalysis for water decontamination and disinfection in rural areas of developing countries (SOLWATER and AQUACAT projects) [53]. Both projects explore development of a solar reactor to decontaminate and disinfect small volumes of water (Fig. 6). Field tests with the final prototypes were carried out in 2005 to validate operation under real conditions [54]. Similar tests have been performed in photoreactors installed in Argentina, Egypt, France, Greece, Mexico, Morocco, Perú, Spain, Switzerland and Tunisia. Fig. 7 shows a photograph of the prototypes. Water from the feed tank is pumped through illuminated tubes connected in series in a CPC solar collector. Electricity is provided by a solar panel and the volume in the feed tank plus tubes is 20 L.

Among the recent projects being carried out at the Plataforma Solar de Almería, the SODISWATER project (http://www.rcsi.ie/sodis/), funded by the European Commission (VII FP) should be mentioned. The strategic goal of this project is the development of an implementation strategy for the solar disinfection of drinking water (SODIS technique [55]) for appropriate, effective and acceptable intervention against waterborne disease in vulnerable communities in developing countries without reliable access to safe water, or in the immediate aftermath of natural or manmade disasters.

The SODIS technique is highly effective against a wide range of pathogens such as *Escherichia coli*, *Vibrio cholerae*, *Salmonella typhimurium*, *Shigella dysenteriae* Type I, *Pseudomonas aeruginosa*, *Candida albicans*, *Fusarium solani*, and the trophozoite stage of *Acanthamoeba polyphaga*. The biocide effect of sunlight is due to optical and thermal processes and a strong synergistic effect at temperatures over 45 °C [55]. In addition to direct killing by UV light, sunlight is absorbed by photosensitizers present in the water, which then react with oxygen producing highly reactive oxygen molecules such as hydrogen peroxide and superoxide dismutase, which have a disinfecting effect. Although SODIS has only been evaluated for a small number of viruses, the efficacy of SODIS for many viral, protozoan and helminthic pathogens prevalent in Sub-Saharan Africa and developing countries in general, remains uncertain.

Another potentially important application of solar photocatalytic disinfection is the control and inactivation of pathogenic species present in the nutritive solution in circulating hydroponic culture (advanced greenhouse agriculture). This is the purpose of the FITOSOL project, which has already proven the feasibility of photocatalytic inactivation of several different phytopathogenic microorganisms at lab and pilot-plant scale (Fig. 8), and under real conditions using solar radiation as a natural source of UV photons.

One of the most important diseases in hydroponic culture is infection by fungal species like *Pythium*, *P. parasitica alpidium bornovanus*, *Fusarium oxysporum* f.sp. *radiciscucumerium*, and other microorganisms, which cause significant losses in greenhouse cultivation. The damage from these microorganisms becomes more severe when water is recirculated. These pathogenic microorganisms are difficult to control once they have entered the agricultural system. Various chemical fungicides (etridiazole, furalaxyl, metalaxyl, benomyl, copper oxalate or oxyquinoline-sulphate) have been tested for pathogen control but have turned out to be phytotoxic in soilless cultures. Chlorine, a universal disinfectant, has provided irregular results and is often phytotoxic. The application of surfactants for controlling *Alpidium bornovanus* and incorporation of 5–7% sodium hypochlorite in the irrigation water have demonstrated limited success. Therefore, non-chemical methods of pathogen control in hydroponic cultures, based on solar photochemical processes could offer a very attractive and innovative solution.

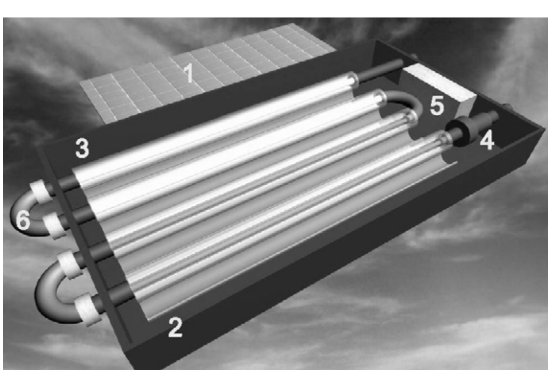

Fig. 6. Conceptual scheme of SOLWATER and AQUACAT photoreactor prototypes (1: photovoltaic panel; 2: Ru(II) photoreactors; 3: supported TiO_2 photoreactors; 4: pump; 5: electrical box; 6: easily opening to photoreactors exchange).

Fig. 7. Final SOLWATER and AQUACAT water (solar photocatalytic) disinfection system installed at Ecole Supérieure de Technologie de Fez (Morocco).

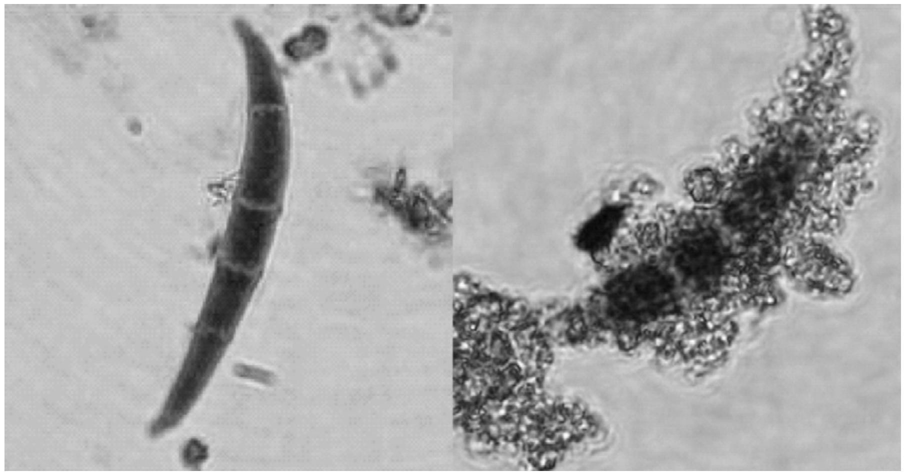

Fig. 8. Macroconidia of *Fusarium equiseti* stained with Malachite Green before (left) and after 5 h of photocatalytic treatment (right) [50].

5. Solar energy and sustainable development: conclusions

The 20th century brought unprecedented development in human history with major breakthroughs in all scientific and technical fields. However, those breakthroughs have not been for free, and in some cases, and from certain points of view, the price paid has been excessive. During the last 100 years, human population has multiplied fourfold (from 1.6 billion people in 1900 to over 6 billion at present). However water consumption has multiplied by nine in the same period and energy consumption by sixteen, and all that with very significant associated degradation of the environment and natural resources. Water and energy, along with air we breathe, are the three elements essential to life and civilization (obviously, linked). At present there is a clear consensus on the impact that this overexploitation of resources is having on the fragile ecosystem of our planet, stretching to the limit (if not already surpassing) the possibilities for sustainability the planet can offer. Therefore, this development, which has been and is clearly unsustainable, must become environmentally friendly, understanding as sustainable development that which is able to fulfil our needs without endangering those of future generations.

To break the currently worrying vicious circle of necessary development and limited resources, the following three essential elements are considered necessary: (a) new ideas that can be deployed by the majority of people; (b) more effective and environmentally friendly innovative technologies; (c) political demand and policies to effectively implement them. In this context, renewable energies in general and in particular, solar energy, because its potential is the highest of all renewables, are called to play a key roll in meeting the goal of sustainable development. Associated technologies could not only guarantee power and water supply, but provide economic development and employment in many Sunbelt areas of the world. Costs are still higher than other conventional technologies, but a strong global effort in research, development and demonstration could rapidly reduce the existing gap. Growing oil price instability and environmental requirements are other factors which contribute heavily to the development of all these solar energy technologies associated with water processes and applications.

Acknowledgments

The authors wish to thank the European Commission (DG XII Research) for its financial assistance within the following EC financed projects: EVK1-CT2001-00102 (AQUASOL), GOCE-036986 (MEDESOL), INCO-032344 (POWERSOL), EVK1-CT2002-00122 (CADOX), GOCE-036882 (INNOWATECH), ICA4-CT-2002-10001 (SOLWATER), ICA3-CT2002-10016 (AQUACAT), INCO-031650 (SODISWATER).

References

[1] IEA. Key world energy statistics. International Energy Agency, Paris; 2007.
[2] International Energy Agency. Energy to 2050, scenarios for a sustainable future; 2003. ISBN 92-64-01904-9.
[3] BP Statistical Review of World Energy, BP p.l.c.; June 2006.
[4] U.S. Crude Oil, Natural Gas, and Natural Gas Liquids Reserves. 2005 annual report, DOE/EIA-0216; 2005.
[5] PennWell Corporation. Oil & Gas Journal, vol. 104.47; December 18, 2006.
[6] Gulf Publishing Company. World oil, vol. 227, no. 9; September 2006.
[7] Petit JR, Jouzel J, Raynand D, Barkov NI, Barnola JM, Basile I, et al. Climate and atmospheric history of the past 420.000 years from the Vostok ice core in Antartica. Nature 1999;399(June (3)):429–36.
[8] Human Development Report 2006. Beyond scarcity: power, poverty and the global water crisis (2006). United Nations Development Programme (UNDP). New York: Palgrave Macmillan. ISBN 0-230-50058-7.
[9] Annan K. We The Peoples. Millennium report of the secretary-general. United Nations, New York; 2000.
[10] Hunter PR, Waite M, Ronchi E. Drinking water and infectious disease. Establishing the links. London: CRC Press; 2003.
[11] Swenson R. The production peaks in petroleum and natural gas: information, misinformation, awareness, and implications. In: Proceedings of the ISES 2005 solar world congress; 2005.
[12] Hoffert MI, Caldeira K, Jain AK, Haites EF, Danny Harvey LD, Potter SD, et al. Nature 1998;395:881.
[13] Wokaun A. Beyond Kyoto: the risks and how to cope. UN framework convention on climate change. Bonn, Germany; 16–25 June 2004. Paul Scherrer Institut; 2004.
[14] United Nations and World Energy Council. World energy assessment: energy and the challenge of sustainability. Washington, DC, USA: Communications Development Inc.; 2000.
[15] United Nations and World Energy Council. In: Goldemberg J, Johansson TB, editors. World energy assessment overview: 2004 update. 2004.
[16] United Nations Development Program (UNDP). Human development report 2006. Beyond scarcity: power, poverty and the global water crisis; 2006.
[17] United Nations. Water for people, water for life—UN world water development report. Paris: UNESCO Publishing; 2003.
[18] El-Dessouky HT, Ettouney HM. Fundamentals of salt water desalination. Amsterdam: Elsevier; 2002.
[19] Wangnick K. 2004 IDA worldwide desalting plants inventory. Report no. 18. Gnarrenburg, Germany: Wangnick Consulting; 2004.
[20] Izaguirre Etxeberria JK. Gestión de Recursos Alternativos. Ósmosis inversa: Desalación de agua. Tecnologia del Agua, special number. Barcelona; 2004. p. 4–11.
[21] García-Rodríguez L. Seawater desalination driven by renewable energies: a review. Desalination 2002;143:103–13.
[22] Alawadhi AA. Desalination—where are we now? GCC countries. Desalination Water Reuse 2002;12(1):12–21.
[23] Al-Shammiri M, Safar M. Multi-effect distillation plants: state of the art. Desalination 1999;126:45–9.

[24] Zarza E, Blanco J. Advanced M.E.D. solar desalination plant: seven years of experience at the Plataforma Solar de Almería. In: Proceedings of the Mediterranean conference on renewable energy sources for water production. EURORED network; 1996.960-90557-0-2 p. 45–9.
[25] Alarcón D, Blanco J, Malato S, Maldonado MI, Fernandez-Ibañez P. Design and setup of a hybrid solar seawater desalination system: the AQUASOL Project. In: Proceedings of the ISES 2005 solar world congress; 2005.
[26] Blanco J, García-Rodríguez L, Martín-Mateos I. Stand-alone seawater desalination by innovative solar-powered membrane-thermal distillation system: MEDESOL project. Desalination, submitted for publication.
[27] García-Rodríguez L, Blanco-Gálvez J. Solar-heated Rankine cycles for water and electricity production: POWERSOL project. Desalination 2007;212:311–8.
[28] Darwish MA. Desalting fuel energy cost in Kuwait in view of $75/barrel oil price. Desalination 2007;208:306–20.
[29] Mussati S, et al. Dual-purpose desalination plants. Part II. Optimal configuration. Desalination 2003/2/10;153:185–9.
[30] El-Nashar AM. Cogeneration for power and desalination—state of the art review. Desalination 2001/4/20;134:7–28.
[31] Alnaser WE, Trieb F, Knies G. Solar energy technology in the Middle East and North Africa (MENA) for sustainable energy, water and environment. Adv Solar Energy 2007;17:261–304.
[32] Aybar HS. Desalination system using waste heat of power plant. Desalination 2004/8/15;166:167–70.
[33] Malato S, Blanco J, Alarcón DC, Maldonado MI, Fernández-Ibáñez P, Gernjak W. Photocatalytic decontamination and disinfection of water with solar collectors. Catal Today 2007;122:137–49.
[34] Gogate PR, Pandit AB. A review of imperative technologies for wastewater treatment. I. Oxidation technologies at ambient conditions. Adv Environ Res 2004;8:501–51.
[35] Blanco J, Fernández-Ibáñez P, Malato-Rodríguez S. Solar photocatalytic detoxification and disinfection of water: recent overview. J Solar Energy Eng 2007; 129:4–15.
[36] Malato S, Blanco J, Alarcón DC, Maldonado MI, Fernández-Ibáñez P, Gernjak W. Photocatalytic detoxification of water with solar energy. In: Goswami Y, editor. Advanced in solar energy an annual review of research and development, vol. 17. Boulder, CO, USA: American Solar Energy Society; 2007, ISBN:. 978-1-84407-314-6p. 130–68.
[37] Mantzavinos D, Psillakis E. Enhancement of biodegradability of industrial wastewaters by chemical oxidation pre-treatment. J Chem Technol Biotechnol 2004;79:431–54.
[38] Blanco J, Malato S, Maldonado MI, Vincent M, Vincent JP, Sánchez M, et al. The Albaida plant: first commercial step in solar detoxification. In: Gaballah I, Mishra B, Solozábla R, Tanaka M, editors. "Global symposium on recycling, waste treatment and clean technology". Proceedings of REWAS 04, vol. II. 2004. p. 1425–36.
[39] Oller I, Malato S, Sánchez-Pérez JA, Maldonado MI, Gernjak W, Pérez-Estrada LA, et al. Pre-industrial-scale combined solar photo-Fenton and immobilised biomass activated-sludge bio-treatment. Ind Eng Chem Res 2007;46:7467–75.
[40] Guimarães JR, Ibáñez J, Litter MI, Pizarro R. In: Blesa MA, editor. Desinfección de Agua. En: Eliminación de Contaminantes por Fotocatálisis Heterogénea. Red CYTED VIII-G; 2001.
[41] Conroy RM, Elmore-Meegan M, Joyce T, McGuigan KG, Barnes J. Solar disinfection of drinking water and diarrhoea in Maasai children: a controlled field trial. The Lancet 1996;348:1695–7.
[42] Caslake LF, Connolly DJ, Menon V, Duncanson CM, Rojas R, Tavakoli J. Disinfection of contaminated water by using solar irradiation. Appl Environ Microbiol 2004;70(2):1145–50.
[43] Wegelin M, Canonica S, Mechsner K, Fleischmann T, Pesaro F, Metzler AJ. Solar water disinfection: scope of the process and analysis of radiation experiments. Water Supply Res Technol Aqua 1994;43:154.
[44] Joyce TM, McGuigan KG, Elmore-Meegan M, Conroy RM. Inactivation of fecal bacteria in drinking water by solar heating. Appl Env Microbiol 1996;62:399.
[45] Rincón AG, Pulgarin C. Bactericidal action of illuminated TiO_2 on pure *E. coli* and natural bacteria consortia: post-irradiation events in the dark assessment of the effective disinfection time. Appl Catal B Env 2004;49:99–112.
[46] Rincón AG, Pulgarin C. Effect of pH, inorganic ions, organic matter and H_2O_2 on *E. coli* K12 photocatalytic inactivation by TiO_2. Implications in solar water disinfection. Appl Catal B Env 2004;51:283–302.
[47] Rincón AG, Pulgarin C. Field solar *E. coli* inactivation in the absence and presence of TiO_2: is UV solar dose an appropriate parameter for standardization of water solar disinfection? Solar Energy 2004;77:635–48.
[48] Rincón AG, Pulgarin C. Photocatalytical inactivaton of *E. coli*: effect of (continuous-intermittent) light intensity and of (suspended-fixed) TiO_2 concentration. Appl Catal B Env 2003;44:263–84.
[49] Fernández-Ibañez P, Blanco J, Sichel C, Malato S. Water disinfection by solar photocatalysis using compound parabolic collectors. Catal Today 2005;101: 345–52.
[50] Sichel C, de Cara M, Tello J, Blanco J, Fernández-Ibáñez P. Solar photocatalytic disinfection of agricultural pathogenic fungi: *Fusarium* species. Appl Catal B Env 2007;74:152–60.
[51] Sichel C, Blanco J, Malto S, Fernández-Ibáñez P. Effects of experimental conditions on *E. coli* survival during solar photocatalytic water disinfection. J Photochem Photobiol A Chem 2007;189:239–46.
[52] Sichel C, Tello J, de Cara M, Fernández-Ibáñez P. Effect of UV-intensity and dose on the photocatalytic disinfection of bacteria and fungi under natural sunlight. Catal Today 2007;129:152–60.
[53] Chapelon A, Herrmann JM. The AQUACAT project/detoxification and potabilisation of water by solar photocatalysis in semi-arid countries. Appl Catal B Env 2004;50:1–5.
[54] Navntoft C, Araujo C, Litter MI, Apella MC, Fernández D, Puchulu ME, et al. Field tests of the solar water detoxification solwater reactor in Los Pereyra, Tucumán, Argentina. J Solar Energy Eng 2007;129:127–34.
[55] McGuigan KG, Joyce TM, Conroy RM, Gillespie JB, Elmore-Meegan M. Solar disinfection of drinking water contained in transparent plastic bottles: characterizing the bacterial inactivation process. J Appl Microbiol 1998; 84:1138–48.